

Design and characterization of a miniature free-swimming robotic fish based on multi-material 3D printing

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Abstract Research in animal behavior is increasingly benefiting from the field of robotics, whereby robots are being continuously integrated in a number of hypothesis-driven studies. A variety of robotic fish have been designed after the morphophysiology of live fish to study social behavior. Of the current design factors limiting the mimicry of live fish, size is a critical drawback, with available robotic fish generally exceeding the size of popular fish species for laboratory experiments. Here, we present the design and testing of a novel free-swimming miniature robotic fish for animal-robot studies. The robotic fish capitalizes on recent advances in multi-material three-dimensional printing that afford the integration of a range of material properties in a single print

task. This capability has been leveraged in a novel design of a robotic fish, where waterproofing and kinematic functionalities are incorporated in the robotic fish. Particle image velocimetry is leveraged to systematically examine thrust production, and independent experiments are conducted in a water tunnel to evaluate drag. This information is utilized to aid the study of the forward locomotion of the robotic fish, through reduced-order modeling and experiments. Swimming efficiency and turning maneuverability is demonstrated through target experiments. This robotic fish prototype is envisaged as a tool for animal-robot interaction studies, overcoming size limitations of current design.

Keywords Biologically-inspired robots · Soft robots · Multi-material printing · Animal-robot interaction

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1 Introduction

Robotics is rapidly gaining traction as a valid experimental approach to provide controllable, customizable, consistent, and reproducible stimuli in animal behavior studies. Robotic stimuli can be engineered to isolate salient variables and to help investigate the neurobiological underpinnings of individual and social behavior (Butail et al. 2015; Kalueff et al. 2014; Krause et al. 2011). The consistency and reproducibility of robotic stimuli may help reducing inter-individual and intra-individual variations in the response of live animals, thereby improving the robustness of experimental trials, toward a more complete statistical characterization, and ultimately reducing the quantity of live animals necessary in the experiments, a tenet of proper and humane animal testing (Russell et al. 1959).

In the context of fish behavior, our research group has contributed to demonstrate the use of robotic fish to

investigate a number of factors related to social behavior, including the role of tail beat frequency and inter-individual spacing in fish schools (Butail et al. 2013, 2014). A variety of biologically-inspired robotic fish have been designed to mimic live species, including mosquitofish (Polverino and Porfiri 2013, b) and zebrafish (Abaid et al. 2012; Butail et al. 2013, 2014; Kopman et al. 2013; Polverino and Porfiri 2013; Spinello et al. 2013). While these prototypes mimicked several morphophysiological features of their live counterparts, their size was at least three times larger, thereby constituting a potential experimental confound in the analysis of sociality.

To address this issue, a number of same-scale fish replicas, controlled externally with various actuators or robotic systems, have been recently proposed. The RoboFish system, described in (Landgraf et al. 2016) and building on the work of (Faria et al. 2010; Swain et al. 2012), utilizes a three-dimensional (3D) printed fish replica modeled after live adult guppies and a mobile robot that actuates the replica with a magnetic interface. In (Phamduy et al. 2014), a 3D printed fish replica is controlled by a robotic platform to mimic the mating swimming patterns of bluefin killifish. In (Bartolini et al. 2016; Butail et al. 2014; Ladu et al. 2015; Ruberto et al. 2016), a robotic platform is utilized to control various zebrafish replicas, featuring a shoal of fish and different body sizes. Although these approaches provide a feasible solution to miniaturize the robotic fish size, they are limited in their capability to provide multisensory cues, often associated with both visual and pressure stimuli. Beyond the demonstrated influence of pressure cues on the interaction between robots and live fish (Marras and Porfiri 2012; Polverino et al. 2013), visual cues from the tail beating have been found to be a critical factor in the spatial preference toward robotic fish (Abaid et al. 2012).

Research into the design of free-swimming biologically-inspired robotic fish has explored various mechanisms for propulsion (Raj and Thakur 2016). Existing designs have explored multi-linked tails actuated by several servomotors (Hu 2006; Phamduy et al. 2015; Yu et al. 2004), single servomotors with compliant caudal fins (Kopman and Porfiri 2013; Kopman et al. 2015; Wang et al. 2015; Wang and Tan 2013), smart materials (Aureli et al. 2010; Cen and Erturk 2013; Chen et al. 2010; Rossi et al. 2011), and fluidic soft actuators (Marchese et al. 2014). However, due to the utilization of commercially available microcontrollers, batteries, or actuators, these free-swimming robotic fish are often several tens of centimeters in length, ranging from 13 to 46 cm (Aureli et al. 2010; Chen et al. 2010; Hu 2006; Kopman and Porfiri 2013; Kopman et al. 2015; Marchese et al. 2014; Phamduy et al. 2015; Yu et al. 2004). The creation of miniature free-swimming robotic fish, of few centimeters in size, presents a number of technical

challenges, especially with regards to the need of housing an on-board power source and enclosing the electronics in a waterproof compartment. The most successful example is likely iSplash-Micro (Clapham and Hu 2014). This robotic fish is 50 mm in length and has been demonstrated to swim up to 10 body lengths per second (BL/s) utilizing a single electric motor. Although very fast, this prototype may not be directly applicable to animal-robot studies, since its body motion is limited to a straight trajectory, tail beat frequencies tend to exceed those of live animals, and the morphology does not exhibit a high degree of biomimicry.

In this paper, we present the design, realization, and characterization of a miniature robotic fish with a novel mechanical design, created utilizing the multi-material 3D printing technique and propelled by a customized solenoid actuator. This untethered robotic fish is envisaged as a tool for animal behavioral research engaging live animals, such as zebrafish and mosquitofish, dealing with complex swimming patterns presenting a stimulus with comparable shape, size, and speed.

A series of experimental studies is conducted to characterize the proposed design and assess its performance with respect to swimming speed and turning maneuverability. A parametric study is performed to examine the tail beat amplitude as a function of the thickness of the joint and tail beat frequency. Drag is measured in a water tunnel at varying flow speed, through a dedicated, custom-made, load cell setup. The thrust production of the robotic fish is investigated in a static water tank using particle image velocimetry (PIV) (Keane and Adrian 1992; Kitzhofer et al. 2012; Scarano and Riethmuller 1999; Thielicke and Stamhuis 2014). The coefficients of thrust and drag estimated from these tests are combined to aid in the interpretation of experimental observations on the forward locomotion of the robotic fish, leveraging a reduced-order dynamical model adapted from the Kirchhoff's laws of motion for vessels near the water surface. Specifically, we investigate the dependence of the forward speed on the tail beat frequency and the joint thickness, drawing comparisons with other prototypes and live fish. Further experiments are conducted to examine turning maneuverability.

The rest of the paper is organized as follows. In Sect. 2, the physical design of the robot is detailed. In Sect. 3, the measurement of the coefficient of drag is described. In Sect. 4, the characterization of the thrust production and the calculation of the coefficient of thrust are presented. In Sect. 5, the results of free swimming tests are presented, along with insight offered by reduced order modeling. In Sect. 6, concluding remarks on the turning ability of the robotic fish and comparisons with the theoretical literature on swimming robots are summarized.

2 Design of robotic fish

The robotic fish prototype and its internal components from the lateral and isometric cross-sectional views, respectively, are shown in Fig. 1. The shell of the robotic fish is an assembly comprised of two parts: the head and the tail. The parts are fabricated on a Stratasys Connex500 3D printer utilizing the TangoBlackPlus and VeroWhitePlus resins (Stratasys 2016). The head is composed of a rigid frontal portion and a flexible part that interfaces with the tail and acts as an o-ring to protect the internal electronics in a waterproof enclosure. The tail is composed of a rigid shell, a thin flexible film (allowing the peduncle to oscillate about a joint), a rigid peduncle (serving the dual purpose of mounting the coil and connecting to the caudal fin), and a flexible caudal fin. The application of multi-material printing enables the robotic fish design to simplify to only two parts, while maintaining the ability to waterproof the electronics and incorporate a joint feature for the actuator.

As shown in the cross-sectional view in Fig. 1, the robotic fish prototype utilizes a custom solenoid to actuate the peduncle and caudal fin. This solenoid is composed of a coil with the dimensions of 10.0 mm for the outer diameter, 7.0 mm for the inner diameter, and 3.7 mm for the height. Four N52 grade neodymium magnets are used with the dimensions of 4.7 mm for the diameter and 1.6 mm for the height. Specifically, three magnets are positioned inside the robotic fish and one is placed on the exterior of the shell to hold the rest in position. To control and power the robotic fish, an ATTiny 85 microcontroller and a 3.7 V (20 mAh) lithium polymer battery are used. The coil is connected to two digital pins on the microcontroller, which can actuate the solenoid, and subsequently the peduncle, by alternating the direction of current flow in the coil. The robotic fish offers an adequate endurance in free

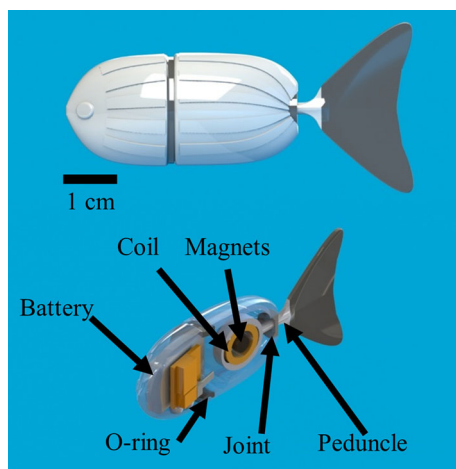


Fig. 1 Illustration of the miniature robotic fish prototype and its isometric cross sectional view, highlighting key internal components

swimming, due to its low power consumption. The typical lifetime of a fully charged battery is ~ 15 min at room temperature. The prototype has enough autonomy to perform several experiments within a single battery cycle. An accurate estimation of the battery life may be performed through a suitable mathematical model of the battery discharge cycle, as suggested in (Phamduy et al. 2016).

Overall, the dimensions of the robotic fish are 2.1 cm in height, 6.6 cm in length, and 1.9 cm in width and the robot dry mass is $m_b = 8.95$ g. The considered robotic fish prototypes use thicknesses of 0.75, 0.85, 1.00, and 1.15 mm for the joint. These thicknesses are selected to ensure the prototypes' durability during handling and afford a wide range of tail beat amplitudes, which should consequently result in varying swimming performance. The selected dimensions might favor the integration of the robotic fish in animal-robot interaction studies, providing repeatable and controllable miniature stimuli to the animal population under investigation.

3 Estimation of the coefficient of drag

The coefficient of drag (Nakayama and Boucher 1998) is measured in a Blazka-type water tunnel, as shown in Fig. 2. The robotic fish prototype is mounted to a thin aluminum rod 4 mm in diameter and is connected to a 10 g load cell (Transducer Techniques, Temecula, CA, USA) measuring forces acting in the direction of the water tunnel to quantify the drag force.

A planar PIV system, FlowMap 1500 (Dantec Dynamics, Holtville, NY, USA), is used to measure the velocity of the flow in the water tunnel upstream of the robotic fish prototype, denoted as u_{WT} . The water is seeded with silver-coated hollow glass sphere particle tracers with a mean diameter of 14 μm (Potters Industries, Carlstadt, NJ, USA). A high-speed camera MegaPlus ES 1.0 (RedLake MASD Inc., San Diego, CA, USA) is used to capture a stream of

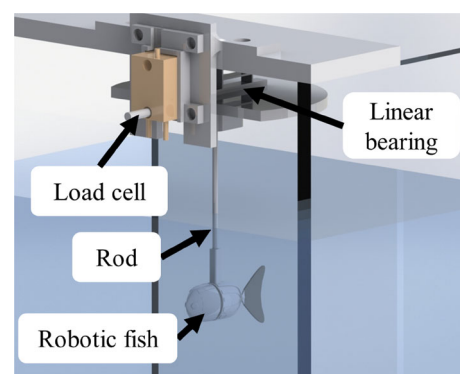


Fig. 2 Illustration of the experimental setup to measure the drag on the robotic fish in a Blazka-type water tunnel

images at a resolution of 1016×1008 pixels and frame rate of 1000 frames per second. Distances in the images are preliminarily calibrated through an image of a ruler with a known inter-distance marks. The PIV analysis implements an adaptive-correlation method on two consecutive images to determine the upstream water speed (Kitzhofer et al. 2012), with a decreasing interrogation window size of 128×128 , 64×64 , and 32×32 pixels and an interrogation window overlap of 50%. Two trials are completed for each nominal flow speed to obtain the following nominal values for u_{WT}^2 : 0, 0.0625, 0.5, 1.0, 1.5, and 2.0 BL^2/s^2 . These values are selected to attain even intervals of the squared velocity near 1 BL/s, which facilitate the quantification of its relationship to drag force.

The relationship between the drag force f^D and the upstream fluid flow u_{WT} is approximated by the classical drag equation (Nakayama and Boucher 1998)

$$f^D = \frac{1}{2} \rho A_r C_D u_{WT}^2, \quad (1)$$

where the dimensionless coefficient of drag is C_D , the wetted area of the robotic fish A_r is $3.2 \times 10^{-3} \text{ m}^2$ and the mass density of water ρ is 1000 kg m^{-3} . We utilize water velocity measurements through PIV and drag force measurements obtained through the load cell to estimate the coefficient of drag, using Eq. (1). A regression line is utilized to quantify the dependence of the fish drag force f^D on the square of the flow speed u_{WT}^2 . As illustrated in Fig. 3, the slope of such regression line is found to be 0.60 kg m^{-1} with a coefficient of determination of $R^2 = 0.65$.

Using Eq. (1) and the slope of the regression, we find that the coefficient of drag is approximately $C_D = 0.38$, which is in line with experiments performed on similar shaped objects, in analogous flow conditions. The latter are encapsulated in the Reynolds number, defined as $\tilde{Re} = \rho \hat{u} L / \mu$, where $\hat{u}$ is the characteristic flow speed (for drag study, $\hat{u} = u_{WT}$), L is the total body length, and $\mu = 10^{-3} \text{ kg m}^{-1} \text{ s}^{-1}$ is the dynamic viscosity of the water at room temperature. The Reynolds number $\tilde{Re}$ for our water tunnel

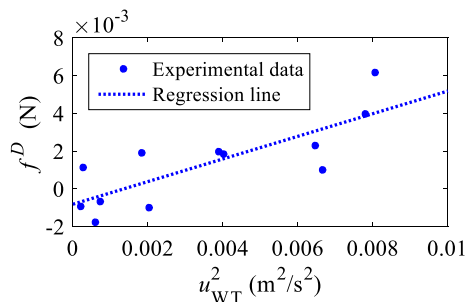


Fig. 3 Experimental data for the drag force versus the square of the flow speed. The *dashed line* indicates a regression line, used to estimate the drag coefficient

experiment ranges from 1089 to 6160. The miniature robotic fish has a similar coefficient of drag to that of a sphere (Morrison 2013), ranging between 1.04 and 0.39, for Reynolds number varying from 10^2 to 10^4 . For a cylinder in axial water flow (Higuchi et al. 2006) with similar dimensions, but in a higher range of Reynolds number from 6×10^4 to 1.8×10^5 , the coefficient of drag is ~ 0.84 , and is expected to decrease in the presence of a streamlined nose and lower Reynolds number (Hoerner 1965).

4 Tail beat motion and thrust production

The experimental setup shown in Fig. 4 is used to examine the tail beat motion and thrust production. The setup consists of the robotic fish prototype anchored by a custom 3D printed clamping device and submerged in a water tank, with dimensions of $61 \times 31 \times 31 \text{ cm}$, as illustrated in Fig. 4. The time-resolved planar PIV system comprises a Phantom high-speed camera V.9.1 (Dantec Dynamics, Holtsville, NY) mounted vertically beneath the water tank and a 5 W RayPower laser (Dantec Dynamics, Holtsville, NY, USA). The water is seeded with silver-coated glass sphere particle tracers with a mean diameter of $44 \mu\text{m}$

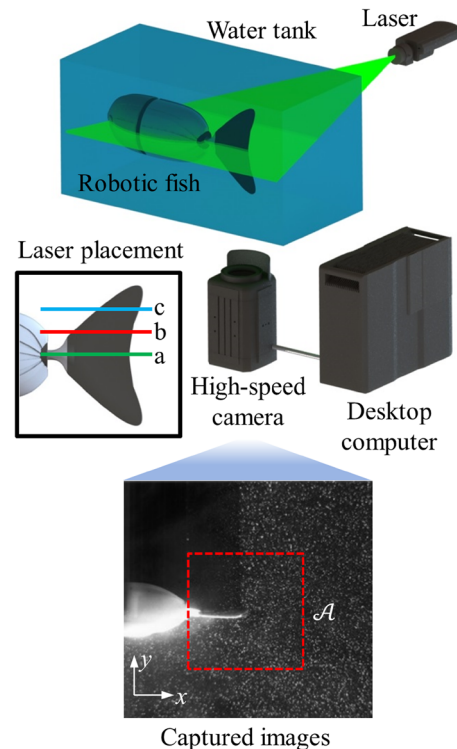


Fig. 4 Illustration of the experimental setup to estimate the thrust produced by the robotic fish through PIV. The $40 \times 40 \text{ mm}$ region of interest for the PIV control volume analysis is identified by the *red dashed box*. The locations of the measurement plane are indicated by lines “a”, “b”, and “c” in the inset; the spacing between lines is 5 mm and line “a” is placed at the mid-plane of the tail

(Potters Industries, Carlstadt, NJ, USA). The high-speed camera captures images at a resolution of 1392×1000 pixels and frame rate of 500 frames per second.

The captured PIV images for a full tail beat cycle are analyzed utilizing “PIVlab” (Thielicke and Stamhuis 2014), an open-source Matlab graphical user interface software. Distances in the image are preliminarily calibrated through an image of a gridded plate with a known 8 mm inter-distance between marks. The PIVlab analysis uses a Fast Fourier Transform multigrid scheme with a decreasing interrogation window size of 64×64 , 32×32 , and 16×16 pixels (Scarano and Riethmuller 1999), an interrogation window overlap of 50%, and a 2×3 Gaussian subpixel interpolation (Thielicke and Stamhuis 2014). The mean velocity field is obtained by averaging the velocity field over one tail beat cycle.

A control volume analysis is utilized for the evaluation of the momentum exchanged by the beating tail on the surrounding fluid (Peterson et al. 2009). Different from (Peterson et al. 2009), we conduct experiments on multiple planes to estimate the role of edge effects, which are expected to significantly contribute to thrust production (Facci and Porfiri 2013). Specifically, we consider three different planes, shown as “a”, “b”, and “c” in Fig. 4, and corresponding to 0, 5, and 10 mm offset from the mid-plane, respectively. The region of interest $\mathcal{A}$ in the PIV analysis is a square domain, measuring 40×40 mm, symmetrically located about the neutral position of the tail (see Fig. 4). The size of the control volume is comparable with previous studies, showing stability of thrust estimation for domains that are approximately twice the tail in length (Peterson et al. 2009; Prince et al. 2010).

Experiments are performed for all the considered pairs of tail beat frequencies (1, 2, 4, and 8 Hz) and thicknesses of the joint (0.75, 0.85, 1.00, and 1.15 mm). The number of frames retained for PIV analysis for the tail beat frequencies of 1, 2, 4, and 8 Hz are 500, 250, 125, and 63, respectively. Five repetitions are completed for each combination of the tail beat frequency and thickness of the joint, along each of the three measurement planes, totaling 240 measurements.

4.1 Effect of the thickness of the joint on the tail beat amplitude

Toward ascertaining the feasibility of the actuation of the robotic fish, the tail beat amplitude A is characterized as a function of the tail beat frequency f and the thickness of the joint. A microcontroller is used to send an AC square wave through the coil to actuate the tail.

The images from the high-speed camera taken during the PIV experiment, as illustrated in Fig. 4, are used to estimate the tail beat amplitude. On each measurement plane, for each

of the five repetitions of a combination of the tail beat frequency and thickness of the joint, the maximum fin tip displacement along the Y -axis, in Fig. 4, is manually measured from select frames of the image set by determining the difference in pixels between the peaks of the tail oscillation. After applying a known calibration factor, the tail beat amplitude is taken as half the peak-to-peak excursion. Figure 5 displays the tail beat amplitude, averaged across five repetitions and three measurement planes, as a function of the tail beat frequency for different joint thicknesses.

The experimental data from the high-speed camera indicates that the tail beat amplitude decreases as the thickness for the joint increases for all tail beat frequencies. For example, across all tail beat frequencies and measurement planes, the tail beat amplitude associated with the thickest joint of 1.15 mm is on average between 63 and 77% of that corresponding to the thinnest one of 0.75 mm.

With respect to the tail beat amplitude, a marked decrease is registered as the tail beat frequency increases for the thinnest joint. Specifically, the tail beat amplitude at 8 Hz is $\sim 79\%$ of the value at 1 Hz. As the joint thickness increases, we observe the presence of a maximum in the tail beat amplitude as a function of the tail beat frequency, whose value increases with the joint thickness. While 0.85 and 1.00 thickness yield a maximum tail beat amplitude at 2 Hz, a larger tail beat frequency of 4 Hz is required to maximize the tail beat amplitude for the thickest joint. This behavior suggests the presence of an internal resonance, whose natural frequencies increases with the joint thickness, which, in turn, causes the stiffening of the tail.

4.2 Thrust estimation

For each measurement plane, the mean thrust per unit width is approximated following (Peterson et al. 2009), where the pressure field is neglected in the evaluation of

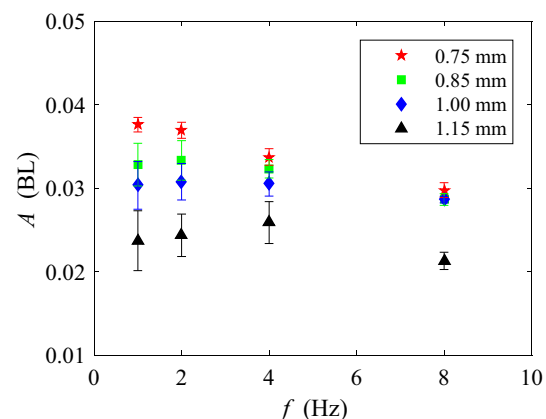


Fig. 5 Tail beat amplitude as a function of the tail beat frequency for different thicknesses of the joint. Error bars indicate one standard deviation

the momentum flux generated by the tail beating. Specifically, we compute the following integrals:

$$\frac{\bar{T}}{d_{f_{\max}}} = \varrho \int_{\partial A} \bar{u} \cdot e_x \bar{u} \cdot dl - \mu \int_{\partial A} e_x \cdot (\nabla \bar{u} + \nabla \bar{u}^T) \cdot dl, \quad (2)$$

where ∂A is the boundary of the control domain, e_x is the unit vector along the neutral tail position, $\bar{u}$ is the mean velocity vector field, dl is the differential perimeter vector oriented along the outward facing normal, $d_{f_{\max}} = 32$ mm is the maximum width of the fin, $\nabla \bar{u}$ is the gradient of the mean velocity, and superscript T indicates matrix transposition.

In Fig. 6a–c, the results of the mean thrust estimation are shown as a function of the oscillatory Reynolds number

Re, defined as $Re = 2\pi f \varrho A L_t / \mu$, where $L_t = 22$ mm is the length of the robotic fish tail measured from the joint. Figure 6a–c report the mean thrust estimation as a function of the oscillatory Reynolds number for different thicknesses of the joint (a) at the mid-plane, (b) at a 5 mm offset, and (c) at a 10 mm offset, corresponding to lines “a”, “b”, and “c” in Fig. 4, respectively.

For Fig. 6a, b, all mean thrust values vary in the range from 10^{-6} to 10^{-3} N, while mean thrust values below 10^{-6} N account for 54% of values in Fig. 6c. Figure 6a–c indicate that thrust production considerably decreases away from the mid-plane, with reductions of few orders of magnitude toward the edge of the tail. We comment that

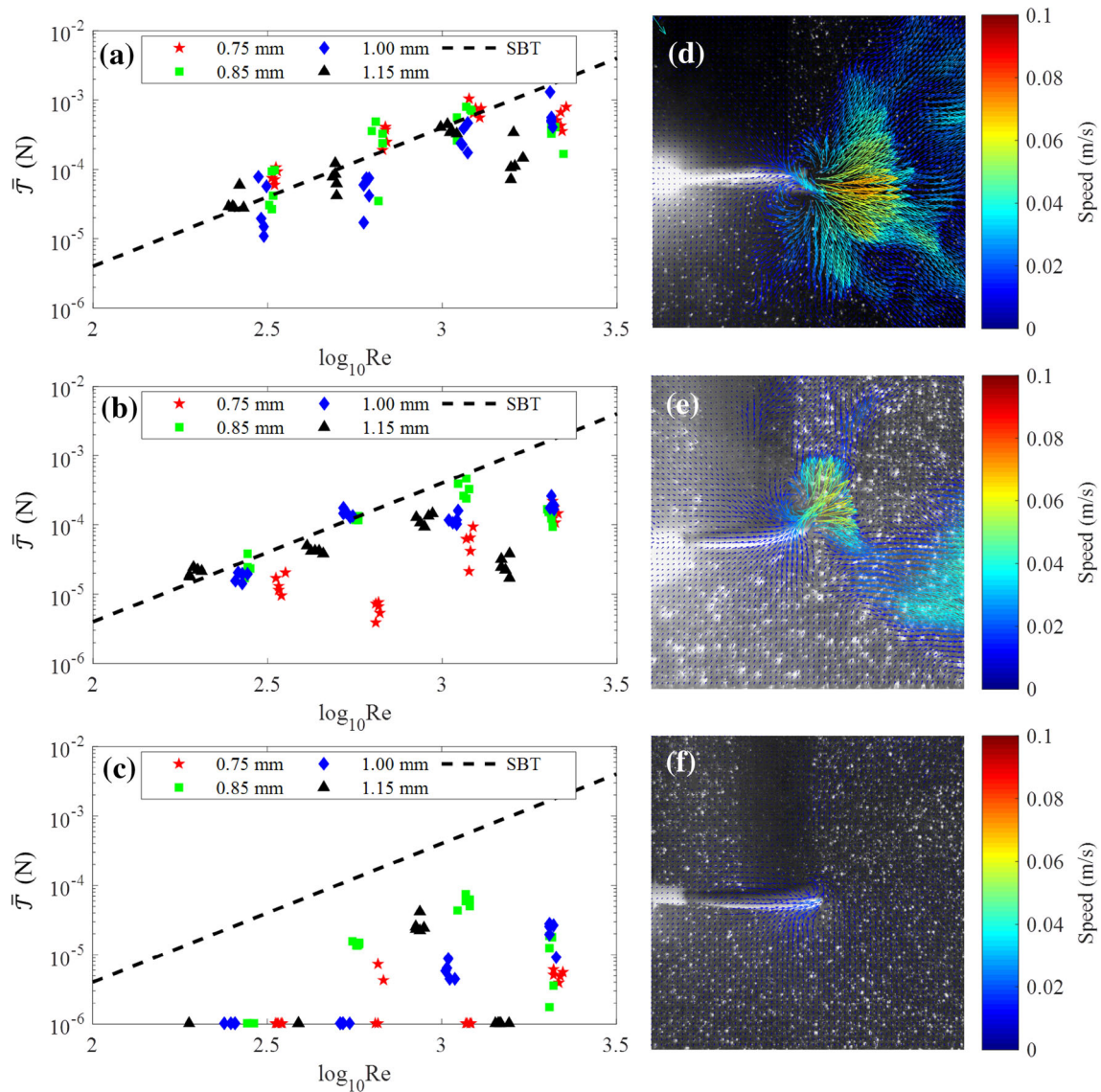


Fig. 6 Estimated mean thrust as a function of the oscillatory Reynolds number for different thicknesses of the joint **a** at the mid-plane, **b** at a 5 mm offset, and **c** at a 10 mm offset corresponding to lines “a”, “b”, and “c” in Fig. 4, respectively. The dashed line indicates theoretical predictions from Lighthill’s slender body theory.

Mean thrust values below 10^{-6} N are saturated at 10^{-6} N for ease of illustration. Representative mean velocity fields from the PIV experiment (**d–f**) corresponding to the offsets in (**a–c**), respectively; the thickness of the joint is 0.75 mm and tail beat frequency is 8 Hz

further increasing the size of the control domain beyond 40 mm produces modest variations of the thrust, within 10%. On the other hand, reducing the size of the control volume may considerably underestimate the thrust.

In Fig. 6d–f, representative mean velocity fields from PIV analysis are shown for the three selected measurement planes. Water motion is largely along the tail axis, causing a net momentum exchange that is responsible for the thrust production. As expected, fluid motion is restricted to a rather confined region in the vicinity of the tip of the tail, whose extent reduces away from the mid-plane. In Fig. 6e, the asymmetry in the flow physics may have been caused by defects in the 3D printed caudal fin that create a slight convex shape, which is more apparent toward the edges.

In Fig. 6a–c, we compare mean thrust results with the classical Lighthill's slender body theory (Lighthill 1971), which has been often used in the literature on robotic fish to estimate thrust production (Aureli et al. 2010; Chen et al. 2010; Kopman et al. 2015; Tan et al. 2010). Following (Facci and Porfiri 2013), this theory can be applied to estimate the mean thrust as

$$\bar{T}_{\text{SBT}} = \frac{\pi d_{f_{\max}}^2 \rho v^2}{16 L_t} \text{Re}^2, \quad (3)$$

where $v = \mu/\rho$ is the kinematic viscosity of the water. From Fig. 6a–c, we note that Lighthill's slender body theory is accurate in predicting thrust production in the mid-plane, while it largely overestimates experimental results toward the edges.

For each experimental trial, consisting of a given combination of the tail beat frequency and thickness of the joint and a select measurement plane, the thrust production is utilized to compute the coefficient of thrust, defined in (Kopman et al. 2015) as

$$C_T = \frac{4 \bar{T} L_t}{\rho v^2 d_{f_{\max}} \text{Re}^2}. \quad (4)$$

We estimate the coefficient of thrust for each combination of tail beat frequency and thickness of the joint by averaging the mean thrust across the three measurement planes and five repetitions. These coefficients of thrust, depicted in Fig. 7, vary within the relatively wide range between 0.06 and 1.00. Predictably, the joint thickness seems to have a rather secondary role on the thrust coefficient, which is instead modulated by the oscillatory Reynolds number. As the Reynolds number increases, we observe a reduction in the thrust coefficient, which indicates that the overall thrust does not quadratically increase with the Reynolds number in the range 214–2145. The dependence on the Reynolds number is satisfactorily captured by the following scaling law:

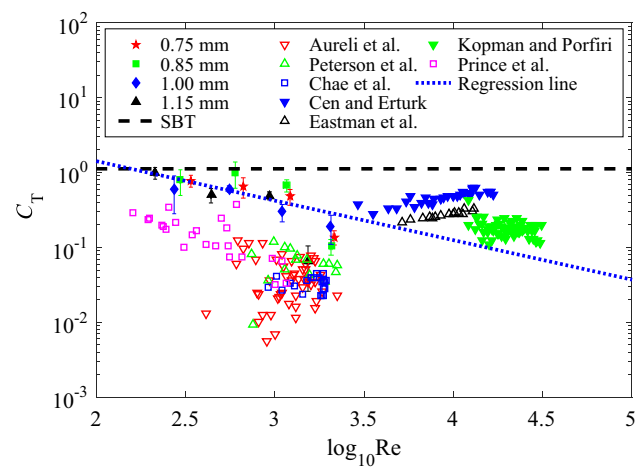


Fig. 7 Coefficient of thrust as a function of the oscillatory Reynolds number and the thickness of the joint. For comparison, the coefficients of thrust from vibrating thin films in the literature (Aureli et al. 2010; Cen and Erturk 2013; Chae et al. 2015; Eastman et al. 2012; Kopman and Porfiri 2013; Peterson et al. 2009; Prince et al. 2010) are shown along with Lighthill's slender body theory (SBT). Standard deviations in our dataset are estimated by grouping the 15 measurements for each combination of tail beat frequency and thickness of the joint with respect to the data gathered at the midplane. Specifically, to each of the measurement at the mid-plane we associate the measurements along the other two planes which have the closest Reynolds number and then average the three values. The five average pairs of coefficients of thrust and Reynolds numbers are treated as independent measurements

$$C_T = 16.15 \text{Re}^{-0.5279}, \quad (5)$$

which is obtained as a linear regression with a coefficient of determination of $R^2 = 0.59$.

Computing the coefficient of thrust through Lighthill's slender body theory in Eq. (3), as $C_{T_{\text{SBT}}} = \pi d_{f_{\max}}/4 L_t$, tends to overestimate the thrust coefficient, in agreement with previous observations (Aureli et al. 2010; Chen et al. 2010). Our results are in good agreement with similar experimental studies on vibrating thin films (Aureli et al. 2010; Cen and Erturk 2013; Chae et al. 2015; Eastman et al. 2012; Kopman and Porfiri 2013; Peterson et al. 2009; Prince et al. 2010), shown in Fig. 7. These experimental studies include ionic polymer metal composites (Aureli et al. 2010; Chae et al. 2015; Peterson et al. 2009; Prince et al. 2010), with a highly comparable Reynolds numbers, and thin piezoelectric (Cen and Erturk 2013; Eastman et al. 2012) and mylar films (Kopman and Porfiri 2013) with a larger Reynolds number range.

5 Swimming experiments

To elucidate the effect of the joint thickness and tail beat frequency on the swimming performance of the robotic fish, we perform a series of experiments. Similar to the

previous analysis, we consider 16 different combinations for the thickness of the joint (0.75, 0.85, 1.00, and 1.15 mm) and tail beat frequencies (1, 2, 4, and 8 Hz).

The robotic fish is powered on upon its assembly and held at the water surface by a custom 3D printed mechanical gripper at the start of the experiment to ensure that the robotic fish would initiate swimming at an initial zero velocity. Experiments are performed in two tanks of dimensions $26 \times 32 \times 51$ cm (for $f = 1$ Hz) and $121 \times 121 \times 51$ cm (for $f = 2, 4$, and 8 Hz) to allow the robotic fish to reach its terminal speed and avoid wall effects.

To effectively capture the robotic fish swimming at tail beat frequencies of 2, 4, and 8 Hz, a DEL Imaging Y-Series 3 high-speed camera (DEL Imaging Systems 2014) is positioned ~ 37 cm above the water surface for a bird's-eye view away from the gripper to ensure the recording of the steady-state swimming at a frame rate of 25, 50, and 100 frames per second (fps), respectively. Likewise, for the cases with a tail beat frequency of 1 Hz, a handheld Canon camera is positioned 74.5 cm above the water surface to record the robotic fish swimming at 30 fps.

Motion analysis is executed with the software Xcitex ProAnalyst (Xcitex 2016), see Fig. 8. We focus on the motion of the robot centroid, which is determined in the computer-aided design model by accounting for all the internal components of the robotic fish. The centroid is located at 22.9 mm from the tip of the robotic fish head, which is approximately at the location of the center of the

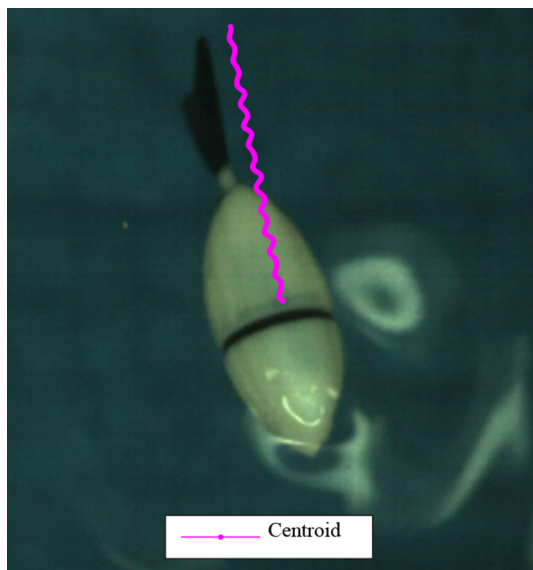


Fig. 8 Illustration of the robotic fish swimming, with superimposed the trajectory of its centroid, tracked using a motion analysis software. The prototype has a joint thickness of 0.85 mm and swims with a tail beat frequency of 8 Hz

o-ring. Such a point is tracked using Xcitex ProAnalyst to ensure high contrast.

The raw position data of the robotic fish centroid are smoothed with a seven-point moving average to remove noise associated with the water surface. The velocity vector is then calculated using a central finite difference on the smoothed position data. Figure 9 displays a typical time trace of the terminal speed, illustrating the presence of a mean value, u_0 , on which a smaller oscillatory component, $\tilde{u}$, is superimposed. As illustrated in Fig. 9, the oscillation is an order of magnitude less than the average component (in Fig. 9, $u_0 = 19.6$ mm/s for a tail beat frequency $f = 8$ Hz and a thickness of the joint of 0.85 mm) and its frequency is comparable with the tail beat frequency of the robot.

In Fig. 10a, the mean terminal speed, calculated by taking the mean of each time trace, is shown as a function of the tail beat frequency for different joint thicknesses. The trend in the mean terminal speed as a function of the tail beat frequency is in line with the literature on robotic fish (Chen et al. 2010; Yan et al. 2008). Specifically, we find that the speed increases with the tail beat frequency and eventually plateaus, beyond 4 Hz. As the thickness of the joint decreases, the average terminal speed increases. For example, at 8 Hz we register a nearly fivefold increase in the mean terminal speed as the thickness of the joint is decreased from 1.15 to 0.85 mm. The highest mean terminal speeds of ~ 19.5 mm/s (0.30 BL/s) are attained for a joint of thickness equal to 0.85 mm a tail beat frequency of 8 Hz. This robotic fish speed is comparable with other larger prototypes ranging approximately from 0.1 to 1 BL/s (Roper 2011).

In Fig. 10b, the oscillatory speed component is shown as a function of the tail beat frequency for different values of the thickness of the joint. The oscillatory speed component is calculated as the amplitude of the fundamental harmonic from a Fourier analysis of the terminal speed data. For all the considered combinations, the oscillatory speed component is approximately an order of magnitude less than that of the mean terminal speed. In Fig. 10c, we display the

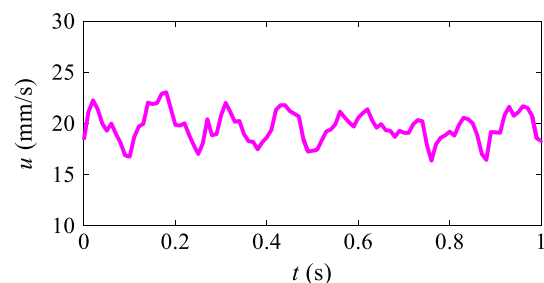
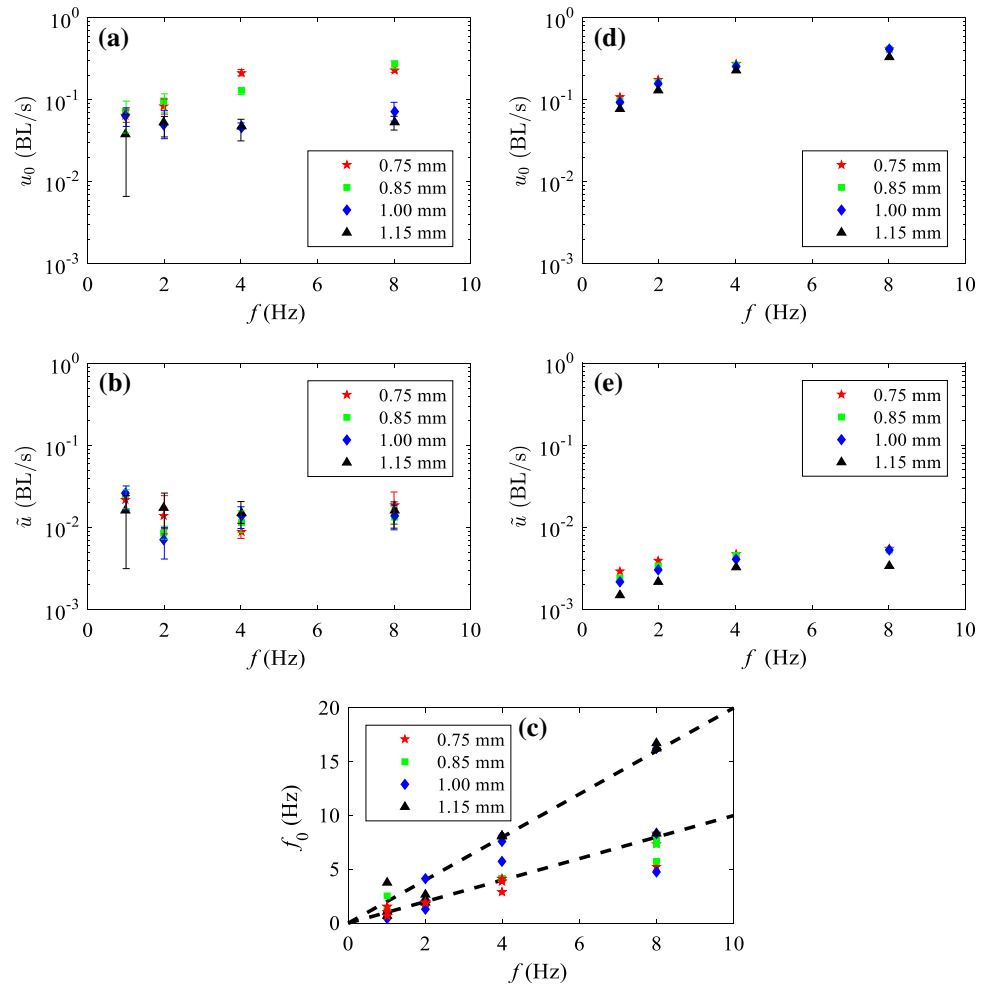


Fig. 9 Time trace of the terminal speed as a function of the time. The waveform is produced with a tail beat frequency of 8 Hz and a thickness of the joint of 0.85 mm

Fig. 10 Experimentally measured **a** average terminal speed and **b** oscillatory speed component as a function of the tail beat frequency and the thickness of the joint. *Error bars* indicate the maximum and minimum value obtained for a tail beat frequency and the thickness of the joint pair. **c** Comparison between the tail beat frequency and the frequency of the fundamental harmonic of the terminal speed for different joint thicknesses. The *dashed lines* identify $f_0 = f$ and $f_0 = 2f$. Predicted **d** terminal speed and **e** oscillatory speed component as a function of the tail beat frequency and the thickness of the joint



fundamental frequency of the terminal speed f_0 as a function of the tail beat frequency. Experimental results seem to cluster around two lines, identifying $f_0 = f$ or $f_0 = 2f$. Most experimental trials for thickness of joint equal to 0.75 and 0.85 mm align on the bisectrix. Only few cases for the thicknesses of 1.00 and 1.15 mm cluster on the other, steeper line.

We utilize a body dynamic equation typical for in-plane motion of vessels near the water surface based on Kirchhoff's equations of motion in an inviscid fluid to predict the steady-state response of the terminal speed (Fossen 1994):

$$(m_b - X_{\ddot{u}})\ddot{u}(t) = -\frac{1}{2}\rho A_r C_D u^2(t) + \frac{1}{2}\rho A_t C_T \dot{\chi}^2(t), \quad (6)$$

where u is the robotic fish speed at the centroid, $X_{\ddot{u}}$ measures the effect of the hydrodynamic of the added mass derivative, A_r is the wetted surface area of the robot in Eq. (1), $A_t = L_t d_{f_{\max}} = 6.9 \times 10^{-4} \text{ m}^2$, and $\chi(t) = A \sin(2\pi f t)$ is the lateral fin tip displacement, neglecting the effect of the tail flexibility. This equation is adapted and simplified from (Kopman et al. 2015) for the case of straight swimming, neglecting the angle of attack and the body dynamic motions

of yaw and sway. This equation should be considered as a first approximation of the tail beat undulation of live animals (Gazzola et al. 2014). Therein, it was shown that a simple, monochromatic function could be used to accurately explain the dependence of swimming speed on tail beat frequency and amplitude, across a wide range of aquatic species from fish to mammals. The added mass derivative is estimated as that of a submerged prolate ellipsoid using Lamb's k factor representation (Fossen 1994), which yields $X_{\ddot{u}} = -4.1 \text{ g}$. In the analysis, we take the coefficient of drag $C_D = 0.38$, as estimated in Sect. 3, the tail beat amplitude from the average values in Fig. 5, and the coefficient of thrust from Eq. (5).

Observing that the oscillatory speed component is much less than the mean terminal speed ($\tilde{u} \ll u_0$) and using standard arguments from perturbation theory (Bellman 2003), the solution for Eq. (6) can be approximated as:

$$u(t) = u_0 + \tilde{u} \cos(4\pi f t + \theta), \quad (7)$$

where θ is a phase offset.

Equation (7) shows that the oscillatory speed component should have a fundamental component at twice the tail beat frequency, as demonstrated in (Kopman et al. 2015).

Our experiments only partially agree with this view, possibly due to the use of the one-dimensional model in Eq. (6) that only accounts for a straight-line swimming. More complex models also account for sway and yaw motions, which have been found to contribute to harmonic content of the robotic fish motion at the tail beating frequency (Kopman et al. 2015). While the visual tracking of the robotic fish centroid is designed to isolate and detect only the forward component of the velocity, it is possible that components of sway and yaw, acting at the tail beat frequency, are spuriously included in the computation, thus masking the oscillatory component at twice the tail beating frequency. Also, the sampling speed of the camera may have hindered the detection of twice the tail beat frequency. Specifically, to detect the 16 and 8 Hz component for the 8 and 4 Hz tail beat frequencies, the sampling frequencies of 100 and 50 Hz, respectively, may not have been sufficient.

From Eq. (7), the mean terminal speed and the oscillatory speed component can be estimated in terms of the parameters of the robotic fish as:

$$u_0 = Af \sqrt{\frac{2\pi^2 A_t C_T}{A_r C_D}} \quad (8)$$

$$\tilde{u} = \frac{\varrho A_t C_T A^2 \pi^2 f^2}{2\sqrt{((m_b - X_{ii})2\pi f)^2 + (\varrho^2 A_t A_r C_T C_D A^2 \pi^2 f^2)/2}}. \quad (9)$$

Using Eqs. (8) and (9), Fig. 10d, e illustrate the predicted mean terminal speed and the predicted oscillatory speed component, respectively, as a function of the tail beat frequency and the thickness of the joint.

In Fig. 10d, the role of the tail beat frequency on the mean terminal speed is accurately predicted, whereby the model seems to properly capture the beneficial role of increasing tail beat frequencies across all joint thicknesses. However, the dependency on the joint thickness seems to be considerably underestimated by the model. Specifically, the predicted mean terminal speed for a thickness of 0.75 mm is only 1.2 and 1.4 times higher than that for 1.15 mm, across all tail beat frequencies, different from experimental data, which suggest a considerably stronger dependence. The experimental data in Fig. 10a indicates that the mean terminal speed with a thickness of 0.75 mm is between 1.5 and 4.4 times higher than that for 1.15 mm, across all tail beat frequencies.

Beyond uncertainties in the measurement of the small terminal speed for thicker joints, we offer the following two explanations. First, both the tail beat amplitude and coefficient of thrust are determined in placid water, and may thus vary during free swimming due to the presence of the upstream flow and its interaction with the body of the robot. Second, the hypothesis of a quadratic

dependence of the drag force on the terminal speed may be strained under the considered swimming conditions. Specifically, Eq. (1) should be considered accurate for very high Reynolds number ($\widetilde{Re} > 10^3$ – 10^4), where the pressure drag dominates the skin drag (Gazzola et al. 2014). At low Reynolds number, the skin drag prevails and the drag scaling law depends on a power of 3/2 for the velocity, instead of 2. In our experiment, the robotic fish swims at the intermediate range of Reynolds number between 10^2 and 10^3 , which might make both drag scaling laws not very accurate for such an intermediate range.

The model is successful in capturing the presence of an oscillatory component in the terminal speed, as shown in Fig. 10e, smaller than the mean terminal speed. However, such a prediction is roughly an order of magnitude lower than the experimental results in Fig. 10b. This discrepancy is likely related to the same arguments at the basis of the presence of a harmonic component of the terminal speed at the tail beat frequency. Specifically, it is possible that the large oscillations in the terminal speed are not only due to the second harmonic predicted by Eq. (7), but also to sway and yaw motions at the tail beat frequencies. Another tenable explanation may be an overestimation of the added mass derivative, resulting in a reduced oscillatory speed component. Specifically, the Lamb's k -factor representation (Fossen 1994) is only an approximation for the added mass derivative and may be further improved through parameter identification, as demonstrated in (Kopman et al. 2015).

6 Concluding remarks

The presented miniature free swimming robotic fish is novel in its mechanical design taking advantage of advances of multi-material 3D printing technique and a customized solenoid actuator for propulsion. Characterization studies have been performed for this robotic fish prototype, including the direct measurement of the drag and systematic analysis of the influence of tail beat frequency and the thickness of the joint on the tail beat amplitude and thrust production. Experimental results on the terminal speed are in agreement with the literature on robotic fish and in line with predictions from reduced order modeling, based on the acquired data on drag and thrust coefficients.

To offer further comparison of the performance of the proposed robotic fish with respect to existing designs, we utilize the arguments proposed in (Gazzola et al. 2014) to elucidate the physics of swimming of the robotic fish. Building on the dataset on swimming robots collated in

(Cha et al. 2016), in Fig. 11 we compare the performance of this robotic fish to existing prototypes actuated by smart materials and electric motors, using the Reynolds number $\widetilde{Re} = u_0 L / \nu$ and the swimming number $Sw = 2\pi f AL / \nu$ (Gazzola et al. 2014).

Specifically, the average tail beat amplitudes obtained through the experiments described in Sect. 4.1 and the mean terminal speeds with corresponding tail beat frequencies and amplitudes obtained through the experiments detailed in Sect. 5 are utilized to compute the values of the Reynolds number $\widetilde{Re}$ and the swimming number Sw . Figure 11 shows that, due to its reduced dimensions, our robotic fish can attain similar values of the Reynolds number to existing prototypes within the laminar regime. With respect to the scaling laws based on live swimmers, our prototype shows a differential performance as a function of the joint thickness. For thin joints, our prototype approaches the swimming performance of live swimmers, whereby it could swim at similar velocities by beating the tail with an equivalent amplitude and frequency. On the other hand, for thicker joints, the swimming performance tends to be lower than live swimmers.

Toward enabling trajectory planning for potential animal-robot interaction studies, the turning maneuverability is explored by varying the ratio of the time spent in the directions of the alternating current flow in the coil. Specifically, this ratio is considered here as the duty cycle of a square wave, where the time spent for a direction of the current flow in the coil is compared to the period of each cycle. That is, for all the swimming tests in Sect. 5, the duty cycle utilized was 50% for all tail beat

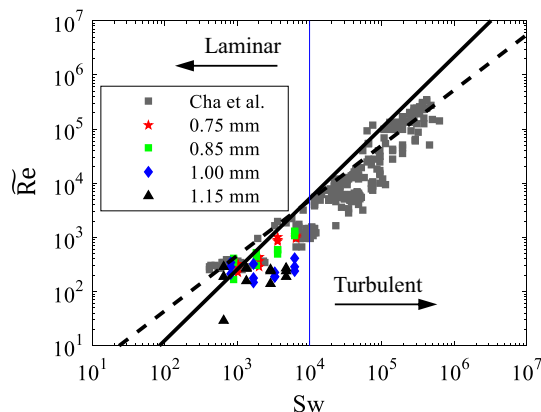


Fig. 11 Comparison of our experimental measurements, with respect to the scaling arguments proposed in (Gazzola et al. 2014), to data from various robotic fish prototypes compiled in (Cha et al. 2016), including prototypes propelled by smart materials and those that are motor-actuated. The solid and dashed lines indicate the scaling laws from (Gazzola et al. 2014) for the laminar ($Sw < 10^4$: $\widetilde{Re} = 0.03 Sw^{1.31}$) and turbulent ($Sw > 10^4$: $\widetilde{Re} = 0.4 Sw^{1.02}$) regimes, respectively

frequencies. The duty cycle for 30, 50, and 70% for an 8 Hz waveform is shown in the inset of Fig. 12. The turning maneuver assessment is conducted in an equivalent experimental setup to the swimming tests. Motion analysis is conducted to ascertain the trajectory of the robotic fish for the various duty cycles, as seen in Fig. 12. The approximate radius of curvature for a duty cycle of 30% is 1.6 BL, for a duty cycle of 50% is 4.4 BL, and for a duty cycle of 70% is 1.0 BL. The mean speed for the duty cycle of 30, 50, and 70% is 0.24, 0.71, and 0.39 BL/s, respectively. A higher radius of curvature for a duty cycle of 50% than 30 and 70% is expected, as 50% is ideally straight swimming.

All the turning maneuverability experiments are conducted in open-loop. In the current implementation, the robotic fish may not operate in closed-loop control due to the absence of a means to regulate tail beating in real-time. The integration of a control system will likely require an increase in the size of the robotic to host a wireless module that could receive feedback about the environment from an overhead camera similar to (Butail et al. 2013). A suitable control technique may be based on a proportional-integral-derivative controller tuned on experimental data through iterative nonlinear optimization strategies (Kopman et al. 2015). Such a technique can be adapted from (Kopman et al. 2015) by acting on the tail beating duty cycle, rather than on the neutral angle of oscillation of the caudal fin.

The flexibility offered by 3D-printing production and computer-aided design can be leveraged to easily construct prototypes with different characteristic dimensions and given swimming performance, by simply scaling the original fish design. For example, if the design target is to have a robotic fish 99 mm in length (i.e., scaled up 1.5 times with respect to the prototype presented in this paper) and a minimum speed of 0.2 BL/s, a scaling law along the lines of (Cha et al. 2016) would indicate that the fish should

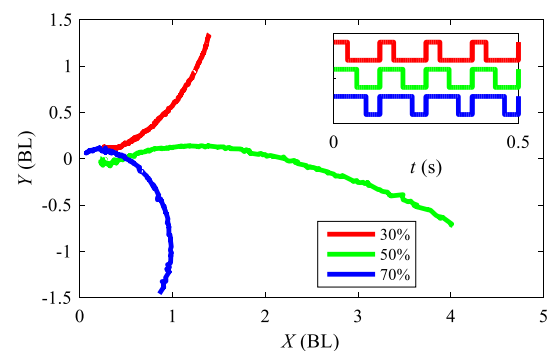


Fig. 12 The turning maneuverability of the robotic fish as a function of the duty cycle of the alternating current flowing in the actuation coil for the case with the tail beat frequency of 8 Hz and thickness of the joint 0.85 mm

swim with a tail beat amplitude of $\sim 6\%$ of its body length, at a frequency of 8 Hz. A simple scaling operation in the computer-aided design will yield the rapid prototyping of such scaled version of the robotic fish.

Future work will explore utilizing a combination of the tail beat frequency, duty cycle, and time duration to create customizable trajectories. These trajectories could include stretches of straight swimming or turning controllable by the duty cycle and fast or slow motion controllable by the tail beat frequency. The development of these trajectories could be utilized to study various topics, including shoaling or mating rituals (Phamduy et al. 2014). Also, more refined representations of the tail beat motion could consider the presence of higher harmonics, which, for example, are important to describe the burst and coast swimming style of zebrafish (Bartolini et al. 2015). The proposed onboard propulsion system could be adapted to generate more complex tail beat undulations, which will be the objective of future research.

We will seek to expand on the dynamic model to enable the description of complex motion patterns, such as those underlying turning maneuvers. To this aim, a hybrid model, which couples the dynamics for the surge velocity described in this paper to a data-driven dynamic description of the yaw velocity, based on the duty cycle of the tail beating, may be considered as an effective modeling strategy. Alternative modeling strategies based on averaging approaches (Wang and Tan 2015) will also be explored. Future work will attempt at the integration of the proposed robotic fish prototype in animal-robot experiments, especially focusing on the zebrafish model organism. Based on experimental evidence in (Abaid et al. 2012; Ruberto et al. 2016), we will seek to closely replicate the color pattern of live subjects and incorporate magnified glass eyes, which have been both found to play an important role on attraction.

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